Padisák, J. (1993): Use of algae for water quality monitoring. In: J. Salánki & V. Istvánovics (eds.) Limnological Bases of Lake Management. Proc. of the ILEC/UNEP Training Course: 73-82. Internat. Lake Environm. Committee Foundation, Shiga.

Use of algae in water quality monitoring

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1. Introduction

After the recognition of the fact that the human use of polluted waters may result in serious sanitary problems, numerous methods of water quality assessment have been developed. Water quality monitoring is carried out for various different reasons ranging from discovering sudden contamination by pesticides, heavy metals, toxic substances, organic pollutants, etc. to detecting long-term global changes like increase of atmospheric deposition, acidification, UV radiation, climatic warming, etc. Each of these influences can be measured by methods other than biological. Several important arguments in favour of biological monitoring are that:

1.) Chemical analyses can qualify and quantify a substance in the best case, but cannot say anything about the biological effects of this substance. What is valid for a single substance may not be true for this substance when it comes in a mixture of substances.
2.) There are many substances that lead to biological reactions in smaller concentrations than can be detected analytically.
3.) The quality of water, such as pH, hardness and oxygen concentration has much influence on toxic substances.
4.) Because organisms have an integrating response to their environment, fluctuations in water quality, which may be missed by intermittent chemical analysis, are recorded.
5.) If we wish to maintain healthy, diverse biological communities, it is more appropriate to monitor the aquatic community rather than physico-chemical variables only.

Algae are the main primary producers in most lakes so it is not surprising that there have been many proposals to use them for monitoring environmental contamination or long-term change. According to a recent summary (Blandin, 1986), after macroinvertebrates (benthic metazoa) and bacteria, algae represent the third most important group applied for monitoring purposes both in freshwater and marine environments. The methods put forward range from the relatively straightforward to those which demand considerable resources and skill. Some methods proved very successful when applied by particular organizations or people, but no one method receives universal acceptance (Whitton, 1991a). Meanwhile, the effectivity of biologically based methods is well reflected in an example described by Harding & Hawley (1991): a survey of 55 sites on the River Wreake catchment in Leicestershire, UK, took one trained biologist less than 10 days of sampling, analysis and reporting, and resulted in the discovery of no less than 10 pollution inputs that had not been detected by chemical sampling.

In the following chapters I give a short summary of the main algal methods that are used to obtain information about different kinds of water quality changes. This includes the description of several approaches. However, a critical review of the algal methods used for water quality monitoring has been beyond the scope of the present paper. Concerning relatively standard methods with algae I refer to the "Blue Booklets" published by the Standing Committee of Analysts of the UK Government Department of the Environment (Standing Committee of Analysts 1983, 1984, 1987, 1990, 1991, in press).

2. Bioassays versus taxonomically based methods

There are basically two different methods in the use of algae in biological monitoring. The first, summarized as "Bioassay Methods" includes the methods in which taxonomic knowledge is not necessary; the information is obtained by exposing algal cultures or natural algal populations to different substances in experimental equipment. The possible substances range from natural nutritional elements, like P or N, to heavy metals, pesticides, herbicides, fungicides and various kinds of industrial pollutant. The basic idea of "Taxonomic Methods" is to collect algal samples from the waters subjected to monitoring and to follow the changes based on the specific information. Both groups of methods have advantages and drawbacks; for example bioassays or metabolic measurements are mostly too expensive for routine monitoring, while taxonomic methods need very skilled staff. They are not strictly separated; the non-taxonomic field methods (2.3) overlap.

2.1 Bioassays

The most attractive feature of bioassay methods is their relative quickness. They are mostly used in river monitoring since rivers, especially in the highly industrialized areas, are more frequently exposed to pollutants like heavy metals or hazardous organic pollutants. In Bavarian (Germany) rivers, such as Danube, Isar and Inn, glass plates (30 x 30 cm) are suspended in the water parallel to the direction of flow. Thirty days after the exposure, the periphyton assemblages are scraped off and analyzed for heavy metals and hazardous organic compounds (Backhaus, 1991).

Fast-changing physiological states, like respiration and photosynthesis, are very suitable for rapid indication of water pollution. When light is absorbed by chloroplasts, the excitation energy can be de-excited by several reactions. De-excitation processes, like electron-transport and fluorescence are in competition. Fluorescence of dark-adapted algae is emitted in a characteristic pattern that is influenced by various parameters of photosynthesis. Hardly any change in photosynthetic reactions will escape from being reflected in one or another fluorescence parameter. This feature makes fluorescence an ideal indicator for early detection and detailed analysis of stress effects on algae (Schreiber et al., 1986). Besides the measurement of oxygen evolution, *in-vivo*-fluorescence has proved to be a powerful method to determine water quality. The automatic algal tests for continuous measurement of water quality, however, have to fulfill some special demands (Merschhemke, 1991):

- For fast indication of changes in the water quality, the assays must be sufficiently sensitive. The incubation period is very short; lasts only for few minutes.
- The assays must be insensitive towards a large number of substances that describe the normal state of the water.
- The test must have a high standard of automation. It must be sure that it runs over several days without being controlled.

Several field applications are described in Sayk & Schmidt (1986), Noack (1989) and Gerhard & Kretsch (1989).

Bioassays have been widely used to estimate the "algal growth potential" and to determine the growth limiting nutrients. The results of many studies (e. g. Demmerle, 1966; Betschart, 1979; Schanz & Juon, 1983, 1984; Lehmacher, 1989) generally prove the growth-promoting effects of waste water additions.

An apparatus for studies of periphyton metabolism is described in Uehlinger & Brock (1991). The system consists of several continuous-flow-through chambers, which can be operated simultaneously. Problems concerning chamber volumes, exposure time etc. are described in the paper cited above. Several applications of the method can be found in Brock et al. (1991).

2.2. Taxonomically based methods

2.2.1 Principles

Taxonomic methods are based on the assumption that different species of algae (or, biota, in general) have their special environmental requirements for growth; therefore, based on their presence or absence we can extrapolate the conditions within which they occur. In other words, species have indicator value and their presence-absence records carry information about the habitat they occur in.

Although the basic principle appears to be very simple, there are numerous theoretical and practical uncertainties concerning its use for monitoring purposes.

For example, some taxa seem to have particularly wide ecological ranges, occurring in contrasting habitats. Does this mean that they are simply very tolerant of a range of conditions, or are a number of physiological races involved, each of more limited range. How do we discriminate between these possibilities? The limited discriminative value of species of wide ecological amplitude is recognized by many authors, and species of more restricted range are given greater significance in assessing water quality. It has been suggested (Leclerq & Maquet, 1987) that an increase in the incidence of poor indicators reflects contradictory data in the literature, with an inevitable reduction in indicator value, but Sládecek (1986) suggests that the rise in poor indicators is because these species have adapted to new conditions. Field observations cannot discriminate between a widely distributed tolerant species or a range of physiological races with different tolerances (Cox, 1991).

Despite the above uncertainties biota, among the algae, are widely used in water quality monitoring. If a group of organisms is to be used as monitor, the group has to fulfill several basic criteria (Round, 1991):

1.) The first and most essential point is that the group of organisms used should be present throughout the studied particular water bodies or their characteristic area. They should grow in a specific, well-defined habitat. They should be easily sampled, present in an abundance. They should be unaffected by life-cycle stages that might leave periods of time when the organisms were not present.
2.) They should react to changes in water quality such that species (or species groups) can be selected to indicate waters of differing (specific) quality.
3.) The species should be easily identifiable (modern floras or faunas must be available), quantifiable, preferably without time-consuming labour and preferably by workers who can be trained to perform

analyses without the need for detailed knowledge of the biology of the organisms.

Among the many possible algal groups for use in monitoring periphytic diatoms and macroscopic algae fulfill best the above criteria. Diatoms are particularly tractable algal subjects because their siliceous cell walls are rarely seriously damaged in removal from natural substrata, unlike for example the attached green algae. As a group they are of almost ubiquitous distribution, allowing comparison over a wide range of habitats, yet individual species have contrasting and restricted distribution ranges. Since, conventionally, their identification relies on cell wall morphology, best revealed in specially embedded mounts, the amenability to permanent preparations removes the necessity for rapid examination or immediate fixation of samples for analysis (Cox, 1991). The main advantage of macroscopic algae (in freshwaters, especially Cyanophyta, Xanthophyceae, Rhodophyceae Chlorophyceae) is that they can be recognized by the naked eye and are sometimes even identifiable on the spot (Dell'Uomo, 1991).

2.2.2. The use of algal indices

In many of the monitoring surveys the collected individual specific data are converted into some index. Indices are the results of attempts to describe water quality on some sort of scale (organic pollution, ammonium, nitrate, phosphate, pH, etc.). Numerous algal indices have been developed during the last decades and according to a recent summary (Whitton et al. 1991) many of them are used for water quality assessment in Europe. They are described in the following publications: Kolkwitz & Marsson (1908), Patrick et al. (1954), Pantle & Buck (1955), Patrick & Hohn (1956), Fjerdingstad (1964), Margalef (1960), Woodiwiss (1964, 1978), Sládecek (1969), Descy (1979), Sládecek (1973), Carlson (1977), Lange-Bertalot (1979), Coste in CEMAGREF (1982), Sumita & Watanabe (1983), Leclerq & Maqet (1987), Sládecek (1986), Watanabe et al. (1988), Leclerq (1988), Runeau & Coste (1988).

This paper is not aimed at discussing the above cited indices in detail, however, a cautionary remark is necessary concerning their use (Cox, 1991): indices can only be as reliable as the ecological data on which they are based.

2.2.3. Multivariate methods

Multivariate methods are increasingly applied for getting more exact information about the relationships between the qualitative/quantitative properties of algal communities and environmental variables. Principal component analysis, (Fernandez-Piñas et al., 1991; Sabater et al. 1992) and cluster analysis (Padisák et al. 1991) were applied successfully for monitoring purposes. Coste et al. (1991) got fairly good correlations among 6 different diatom indices applied to 1498 river samples. Their result supports the use of indices in monitoring. They also tested by means of principal component analyses how the different indices conform to the obtained parallel physico-chemical analyses.

2.2.4. Coding and data bases

Coding systems of algae for monitoring and survey purposes have been in use since the early 1970s. It is essential to use codes corresponding to different taxa. A variety of systems have been adopted for coding freshwater algae (for example Williams et al. 1988; Marelius, 1976; Whitton et al. 1978, 1979; Maitland, 1977; Klasvik, 1974; Coste et al. 1991; Pyrigel, 1991, etc.) but none appear to have obtained especially wide acceptance. According to Whitton (1991b) an ideal coding system for monitoring purposes should fulfill the following criteria:

1.) It should be relatively easy to use by people of differing taxonomic expertise.
2.) It should permit all organisms to be scored, not merely those which can be named in full.
3.) It should be sufficiently flexible that modifications can be made easily with changes in views about taxonomic limits.
4.) It should permit easy interchange of data stored using other coding systems.

Computer problems and methods for handling large databases and the exploration of their information content will become one of the major difficulties in connection with algological monitoring. A pilot study (Padisák et al., 1991) on an already existing data bank showed that, however much the original single data-sets differ, large data banks can be useful in searching for variables that can be used for monitoring water quality. Simple variables (e.g., the ratio of diatoms to non-diatoms) and multivariate methods can be applied with a good measure of success.

2.3. Non-taxonomic field methods

Several methods that are widely used for monitoring involve neither taxonomic identification nor installation of experiments. In most cases they aim to measure the standing crops as cell or individual density, biomass, etc. Measurement of the chlorophyll-a content in field samples is perhaps the most widely used method (Standing Committee of Analysts 1983). There are a lot of analyses on the accuracy of the measurement as well as about the factors that influence the chlorophyll-biomass relationship (see Vörös & Padisák, 1990). Margalef's (1960) pigment diversity index is also based on pigment measurements and it is used for monitoring rivers in Portugal (Ferreira, 1991). Several other methods are mentioned in Whitton et al. (1991).

3. Algae as indicators of different environmental hazards

Algae proved to be rather responsive to various environmental changes of human origin. In this chapter the responsiveness of algae to changes in saprobity, trophic change, acidification, etc., is discussed briefly.

3.1. Saprobity, organic pollution

Biological methods for water quality monitoring originate from the saprobic system ("Saprobiensystem") developed by Kolkwitz and Marsson (1908, 1909). Sets of indicator species assigned to different saprobic zones are considered to represent primary biological delimitation for these zones. In the State Norm of the former Czechoslovakia saprobiological characteristics are compiled for more than 4000 organisms, among them 1509 algal taxa (incl. blue greens) and 256 colorless flagellates. It should be mentioned here that the saprobic system and mostly the application of autotrophic organisms has often been criticized. All modifications of the saprobity estimation are comparisons of the floristic and/or faunistic composition of a sample with the floristic and/or faunistic composition found in and cited for the prototype localities of the established saprobity degrees.

The saprobic system is (and probably remains) purely empirical. The distribution of indicators in ecological situations corresponding to different zones of saprobity serves as the main source of information to calibrate or revise the list of indicators.

Several saprobity scales were proposed for numerical handling of the data. The most simple is that proposed by Pantle & Buck (1955), and later extended by Sládecek (1969) and modified by Marvan (1969) and Marvan et al. (1980). For a guide and comments on calculating the saprobic indices see Marvan (1991) and Sládecek et al. (1981). Positive and good correlations between the above saprobic indices and BOD_5, the common measure of organic pollution, have repeatedly been confirmed by authors from different countries (Zelinka & Marvan, 1957).

According to Marvan (1991) methods based on the tolerance versus sensitivity to pollution (cf. Lange-Bertalot, 1978, 1979) seem to have a further advantage in that they allow an unambiguous estimation of the pollution degree without the necessity to add further criteria: if a sample contains species that are (according to the definition) unable to tolerate heavier pollution, then the water must be less polluted. The opposite conclusion "if more sensitive and less tolerant species are absent, the pollution exceeds a given limit", is questionable. In fact, here we have to do with negative instead of positive indicators.

3.2. Inorganic nutrient load, trophic states

The trophic state of waters has been traditionally determined by comparing the field records to one of the available trophic scales. Numerous trophic scales have been published, therefore such comparisons can be made based on algal numbers (Felföldy, 1974), phytoplankton biomass (Vollenweider, 1968; Winberg, 1975; Wetzel, 1975; Munawar & Burns, 1976), carbon-equivalent of phytoplankton biomass (Wetzel, 1975; Gorlenko et al. 1977), chlorophyll-a (Felföldy, 1974, Wetzel, 1975, Forsberg & Ryding 1980) and primary production (Winberg, 1961; Rodhe, 1969; Felföldy, 1974, 1977; Likens, 1975; Wetzel, 1975, Golenko et al. 1977). These trophic scales often overlap each other; see G.-Tóth & Padisák (1982, 1983, $1984_{a,b}$) for comparisons.

During eutrophication composition of the phytoplankton flora and especially contribution of different algal groups to total biomass also changes, therefore, it is theoretically possible to follow eutrophication based on taxonomic records. Several early attempts were made (Thunmark, 1945; Nygaard, 1949) but these methods did not receive wide acceptance compared to saprobic estimations (3.1). Several recent approaches are dealt with in the next chapter (3.3). Since, for example, diatoms were proved to be sensitive to trophic levels and especially phosphate (Descy & Coste 1989, 1990) algal taxonomic methods in monitoring trophic changes will probably become more widespread than they are currently.

3.3. Eutrophication and management of planktonic algae

Eutrophication is generally understood to refer to enrichment of biological systems by nutrient elements, notably nitrogen and phosphorus. The OECD (Organization for Economic Cooperation and Development) has defined eutrophication as "the nutrient enrichment of waters which results in stimulation of an array of symptomatic changes among which increased production of algae and macrophytes, deterioration of water quality and other symptomatic changes are found to be undesirable and interfere with the water uses (Connell & Miller, 1984)". The eutrophication models, for example the best-known published by Vollenweider & Kerekes (1982), demonstrate that the greater is the external load of phosphorous then the greater is the quantity of algal chlorophyll that will be supported. However, attempts to reverse the effects of eutrophication have had conspicuously variable results. The reasons are various; in Reynolds' (1992) recent review the needs to distinguish rate-limitation from capacity limitation, to understand which is more manageable and why, to discern the mechanisms of internal recycling and their importance and to appreciate the respective role of physical and biotic components in local control of algae dynamics are emphasized. A provisional "decision tree" (Fig. 1) for lake restoration and management is also available in the paper (loc. cit.).

3.4. Saprobic and trophic overlaps
Either because natural waters receive in parallel both organic and inorganic pollutants or because the organic material is quickly transferred to inorganic substances, saprobic and trophic changes often overlap both in time and space. In most of the cases it is difficult, if at all possible, to decide what is behind the presence of this or that indicator species: saprobic or trophic change. That is why recent works on algal indicator species try to elaborate scales in which both saprobic and trophic levels are represented.

Schiefele & Schreiner (1991) have recently described a combined trophic state and pollution indicator system and used it for qualifying stream-water quality based on diatom data. Dell'Uomo's (1991) specific index for eutrophication/pollution (E/P index) is based on the five limnosaprobic levels reported by Sládecek (1973), but incorporates phenomena of eutrophication and pollution. Indicator values of riverine macroscopic algae are given in the reference cited above.

3.5. Acidification
Compared to trophic and saprobic changes, acidification has been a slower process that became apparent recently. That is why our recent knowledge is coming from rather diverse sources; case studies are available but their number has not been enough for outlining some generalized concept.

Hustedt (1938/39) classified the various diatom species with respect to their empirical pH optimum (groups: acidobiontic, acidophylous, indifferent, alkaliphylous, alkalibiontic). On the basis of this classification and an index (Index B) described by Renberg & Hellberg (1982) the diatom community can be described by a number that is based on the pH preferences. This method has been used successfully in paleolimnological studies (Renberg & Hellberg, 1982) and a positive correlation was found between the index B and the measured pH in Central European sites (Arzet, 1987). In Schreiner's (1989) studies the index B correlated better with the alkalinity than with the measured pH.

Coring (1988) found a reduction of algal species and a reduction of growth of diatoms in acidified streams. Scandinavian experiences (Lindstrom, 1991) also support the impoverishment and loss of biota due to acidification.

Several studies conclude that the effect of acidification can be overdominated by saprobic effects (Hofmann, 1987) or that chemical factors (aluminum, iron, heavy metals, DOC) often interfere (Schreiner, 1987; Steinberg & Putz, 1991).

It is suggested in many of the above studies and in Cox's (1991) review that the indicator-value of the species needs reconsideration. A recent pH qualification of some periphytic algae (incl. blue-green algae, green algae and several others) is available in Lindstrøm (1991).

3.6. Salinity
As a consequence of various reasons, such as increased atmospheric deposition, winter-deicing, summer-de-dusting, industrial activity, etc., there is a danger of salinity increase in waters. Water salinity has long been considered as a main factor affecting diatom communities (Sabater et al., 1991; Meiner and Barlas, 1987; Schmid, 1976): they may become important monitors in the future.

3.7. Heavy metals
A variety of methods has been developed for use of algae to monitor heavy metal contamination (Whitton, 1984). The simplest is the use of tissue analysis as an indicator of the environmental concentration of the contaminant. The advantage of this approach for monitoring heavy metals is presented in Whitton (1991a). A standard "package" (Standing Committee of Analysts, 1991) of ten genera/species of plants suited for monitoring heavy metals in UK waters includes three algae (*Lemanea, Cladophora glomerata, Nitella*). Algae are in many cases at a disadvantage to bryophytes, however, because they accumulate much less metal per unit dry weight (Kelly & Whitton, 1989). Considerable periphyton/water accumulation factors (Cd: 20,000-30,000; Cu: 20,000-70,000; Hg: 3000-10,000; Zn: 13,000-40,000; Pb: 30,000-100,000) were found in Bavarian rivers (Backhaus, 1991) after a 30 day exposure time. *Cladophora glomerata* (Whitton 1991a) has the advantage over bryophytes that the rate of change of its metal concentration as a response to external metal concentration is more rapid.

Specific differences in heavy metal tolerance of green microphytic (*Cladophora, Stigeoclonium, Hormidium*) green algae assisted in providing an explanation for the *Cladophora* in eutrophic rivers (Whitton, 1970, 1980) and morphogenetic consequences of heavy metal exposure are also proved (Harding & Whitton, 1976; Say et al., 1977).

Analysis of *Cladophora glomerata* has also proved useful in monitoring ^{125}I and ^{131}I in several British rivers (Howe & Hunt, 1984; Howe and Lloyd, 1986).

3.8. Pesticides
Nowadays a huge amount of herbicidal substances comes into the water. The enormous complexity of such a cocktail of substances can be analyzed only partially by chemical or physical methods. Algal strains appeared useful in testing chemical substances with respect to their toxicity in bioassays (Merschhemke, 1991); and there are scattered reports on pesticide accumulation by *Cladophora* (e.g., Ware et al., 1968). A water/periphyton accumulation factor of 8000 fold was found for hazardous

organics. Green algae appeared to be more sensitive than diatoms, and diatoms more than heterotrophic microorganisms such as bacteria or fungi. A bioassay method is mentioned in Backhaus (1991).

4. The "zero" or "natural reference" state

There is a large diversity of human impact that affects the earth's ecosytems. In surface waters eutrophication and deteriorating saprobity are particularly well documented, but other local contaminants, like heavy metals, hazardous organics, etc. also have their influence. Nowadays many of the threatening dangers are of global type; acidification, atmospheric deposition, increased UV-radiation and climatic warming are the best known ones and there is a good reason to suppose that we will have to face yet other threats that have been unknown. Another indication of performing such studies is to provide the scientific background of large-scale environmental manipulations before construction begins (big reservoirs, irrigation systems, etc.). The detection of the global effects has been more problematic because they act in the long term and in the long range. The design of such experiments differs from the routine monitoring in numerous ways, for example:

- test-objects (lakes, rivers) should be as uninfluenced as possible; free of local human effects;
- background variables must be measured in large numbers and by the best possible methods (any future methodological change threatens the comparability);
- biological information must be obtained at the highest taxonomic accuracy possible.

Such studies began in Sweden in the 1980s: aims, reasoning of the sampling design, and preliminary results are available in Fängström & Willén (1987), Willén (1990), Persson et al. (1989) and Willén et al. (1990).

Lindstrom's (1991) analysis inevitably proves that sufficiently reliable and previously obtained algal data are applicable in evaluating effects of later influences and evidence exists (Padisák et al., 1991) that even inhomogeneous algal data-bases are suitable to trace environmental change in clear-cut cases.

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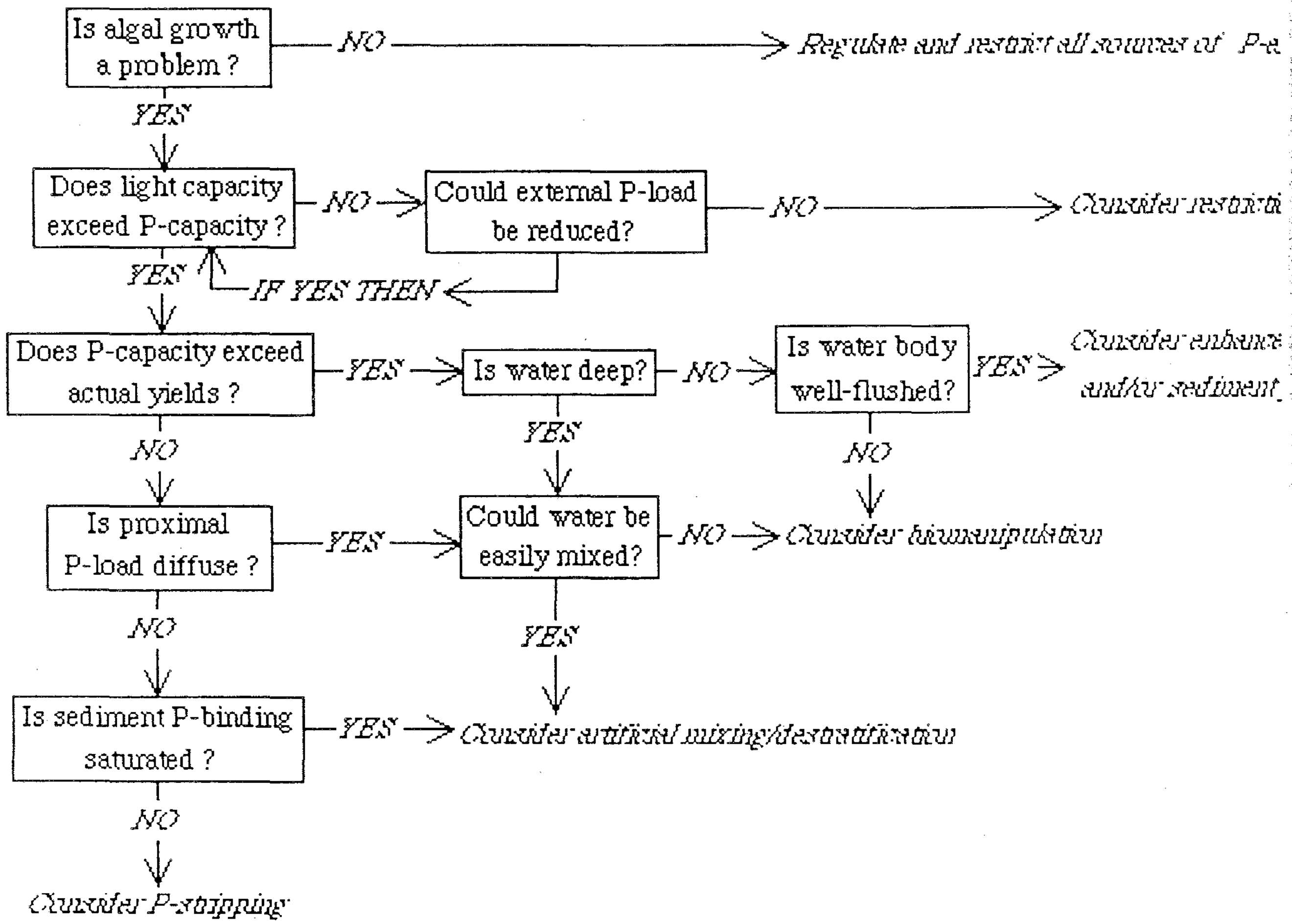

Fig. 1: »Provisional "decision tree" for lake restoration and management. Each of the boxes requires to be quantified and no option is exclusive. Future research might usefully concentrate upon the refinement of this approach and its application. « (Reproduced from Reynolds [1992] fig. 12; with the permission of the originator and the FBA.)